Revista Brasileira de Ciência do Solo
ISSN: 0100-0683
revista@sbcs.org.br
Sociedade Brasileira de Ciência do Solo
Brasil

Guarçoni, André; Moreira Sobreira, Fabrício
Classical Methods and Calculation Algorithms for Determining Lime Requirements
Revista Brasileira de Ciência do Solo, vol. 41, 2017, pp. 1-11
Sociedade Brasileira de Ciência do Solo
Viçosa, Brasil

Available in: http://www.redalyc.org/articulo.oa?id=180249987029

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Revista Brasileira de Ciência do Solo

Division - Soil Use and Management | Commission - Lime and Fertilizer

Classical Methods and Calculation Algorithms for Determining Lime Requirements

André Guarçoni[(1)*] **and Fabrício Moreira Sobreira**[(2)]

[(1)] Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural, Venda Nova do Imigrante, Espírito Santo, Brasil.
[(2)] Instituto Federal Catarinense, *Campus* Araquari, Araquari, Santa Catarina, Brasil.

ABSTRACT: The methods developed for determination of lime requirements (LR) are based on widely accepted principles. However, the formulas used for calculation have evolved little over recent decades, and in some cases there are indications of their inadequacy. The aim of this study was to compare the lime requirements calculated by three classic formulas and three algorithms, defining those most appropriate for supplying Ca and Mg to coffee plants and the smaller possibility of causing overliming. The database used contained 600 soil samples, which were collected in coffee plantings. The LR was estimated by the methods of base saturation, neutralization of Al^{3+}, and elevation of Ca^{2+} and Mg^{2+} contents (two formulas) and by the three calculation algorithms. Averages of the lime requirements were compared, determining the frequency distribution of the 600 lime requirements (LR) estimated through each calculation method. In soils with low cation exchange capacity at pH 7, the base saturation method may fail to adequately supply the plants with Ca and Mg in many situations, while the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents can result in the calculation of application rates that will increase the pH above the suitable range. Among the methods studied for calculating lime requirements, the algorithm that predicts reaching a defined base saturation, with adequate Ca and Mg supply and the maximum application rate limited to the H+Al value, proved to be the most efficient calculation method, and it can be recommended for use in numerous crops conditions.

Keywords: pH, calcium, magnesium, deficiency, overliming.

***Corresponding author:**
E-mail: guarconi@incaper.es.gov.br

Received: February 3, 2016
Approved: September 14, 2016

How to cite: Guarçoni A, Sobreira FM. Classical methods and calculation algorithms for determining lime requirements. Rev Bras Cienc Solo. 2017;41:e0160069.
https://doi.org/10.1590/18069657rbcs20160069

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INTRODUCTION

Most land used for agriculture in Brazil has inadequate chemical properties in its natural state for complete development of plants. Among these properties are high acidity, high levels of exchangeable acidity (Al^{3+}), and deficiency of the nutrients Ca and Mg. In this context, liming is a necessary practice so that these soils can produce high crop yields, reducing acidity, reduces the toxic effect of Al^{3+} and Mn^{2+} and providing Ca and Mg to plants (Sousa et al., 2007; Prezotti and Guarçoni M, 2013). Furthermore, Alvarez V and Ribeiro (1999) reported that liming is essential for improving the plant root environment and is probably the primary condition for increasing crop yield.

There are three main methods used to calculate lime requirements (LR) in Brazil, described in classical studies on the subject, including the SMP buffer method, the base saturation method, and Al^{3+} neutralization and elevation of Ca^{2+} + Mg^{2+} method.

The SMP buffer method is used in southern Brazil (Rio Grande do Sul and Santa Catarina), characterized by measuring the pH of the suspension when a buffer solution is placed in contact with the soil (Raij et al., 1979). The LR needed to achieve a pH of 5.5, 6.0, or 6.5 is estimated by means of calibration tables prepared for $CaCO_3$ for regional soils.

The base saturation method (BSAT) seeks to increase the base saturation of the soil to pre-defined values for different crops. As consequence of lime application, there is also in increase in pH to levels estimated by formulas such as those of Catani and Gallo (1955) and Raij et al. (1983), which characterize the correlation between base saturation and pH. In this method, the actual base saturation of the soil and the desired saturation are considered, as well as the CEC at pH 7 (T) (Raij et al., 1983). Because the method is highly dependent on T, the method may recommend low application rates, insufficient to supply the plants with Ca and Mg if the soil T is excessively low.

The method of Al^{3+} neutralization and elevation of Ca^{2+} + Mg^{2+} seeks to neutralize the exchangeable acidity (Al^{3+}) present in the soil and provide Ca and Mg based on crop needs (Alvarez V and Ribeiro, 1999). The method was presumably established as a way to increase the application rate recommended by the method that used only the principle of soil Al^{3+} neutralization, since according to Nolla and Anghinoni (2004) it would not be adequate to achieve sufficient pH values.

The rates calculated by the method of Al^{3+} neutralization and elevation of Ca^{2+} + Mg^{2+} always supply the plants with proper amounts of Ca and Mg if the value of X is accurately calibrated, where X is the plant demand for Ca + Mg. However, according to Sousa et al. (1989), the liming rates calculated by this method may increase the soil pH to very high levels if the T value is below 4 $cmol_c$ dm^{-3}, the organic content is less than 10 g kg^{-1}, or the clay content is less than 300 g kg^{-1}.

Adoption of the correct lime requirement and application recommendation model depends on the soil properties of each region, in conjunction with the principles adopted by the researchers, seeking to select the procedure that best fits the prevailing acidity conditions at the site (Nolla and Anghinoni, 2004). However, a concern is that the formulas to calculate the lime requirements have evolved little over the decades, considering that despite the theoretical adequacy of the methods generated, they are recurrently ineffective in some specific situations.

The methods of base saturation and Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents used to determine the LR may be inadequate in some conditions but because of a different effect; while the first may generate rates that would not suitably supply the plants with Ca and Mg, the second could result in soil pH values exceeding the appropriate range. One attempt to use the best of what is contemplated by these two methods would be to group them in an algorithm in order to obtain more suitable rates for a variety of situations.

Algorithms have been known for millennia, the first being articulated, most likely, by Euclid in 300 B.C. More recently, with the advent of computer technology, the algorithm has become widely used in software, being conceptualized as "any well-defined computational procedure that takes some value or set of values as an input and produces a value or set of values as an output" (Cormen et al., 2002). However, the use of algorithms should not be restricted to software, since the simplest may be processed without the use of computers and are nothing more than "a finite sequence of steps (instructions) to solve a particular problem" (Ferrari and Cechinel, 2008).

The objective of the present study was to compare the liming requirements calculated by three classical formulas and three algorithms, defining those most appropriate according to the Ca and Mg supply to the coffee crop, and the smaller possibility of causing overliming.

MATERIALS AND METHODS

The study was carried out using a database of analytical results from 600 soil samples collected in coffee plantings from different regions of the state of Minas Gerais, Brazil. The analytical results consisted of routine analysis, i.e., acidity characteristics, available and exchangeable forms of nutrients, organic matter (OM), and remaining phosphorus (P-rem). The following methods for analysis were used, as described by Defelipo and Ribeiro (1997): pH(H_2O) 1:2.5 (v/v), organic matter content, oxidation with potassium dichromate (Walkley-Black method), P and K (Mehlich-1), Ca^{2+}, Mg^{2+} and Al^{3+} (1.0 mol L^{-1} KCl), H+Al and CEC pH 7 (T), 0.5 mol L^{-1} Ca $(OAc)_2$ extractant, pH 7.0. The method proposed by Alvarez V et al. (2000) was used to determine P-rem: P in solution after stirring 60 mg L^{-1} of P in 10 mmol L^{-1} $CaCl_2$ for 1 h in a soil:solution ratio of 1:10.

From the results of 600 soil samples, the lime requirements (LR) were calculated by six different methods, considering a coffee crop, and the results were expressed in Mg ha^{-1} of limestone effective calcium carbonate equivalent (CCE) 100 % (total area and incorporated in up to 0.20 m of the soil).

There are three classical formulas to calculate LR: (1) the formula of the base saturation method, "BSAT" (Raij et al., 1983); and two calculation formulas of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents - (2) "MG1" (CFSEMG, 1989), using the values of Y and X proposed by Alvarez V and Ribeiro (1999), and (3) "MG2", proposed by Alvarez V and Ribeiro (1999).

We also evaluated three calculation algorithms: two that used a decision-making process between the BSAT and MG2 formulas, with different input criteria: lower LR application rate (4) "ALG1", and higher LR application rate (5) "ALG2", but using the same minimum and maximum rate limits; and one algorithm which used the BSAT method and the formula used for elevation of Ca^{2+} and Mg^{2+} in the soil proposed by CFSEMG (1989), with a maximum limit for the recommended application rates (6) "ALG3" (Table 1).

In the calculations, the values of V = 60 %; X = 3.5, and m_t = 25 % were used, suggested for the coffee crop by Alvarez V and Ribeiro (1999).

The maximum and minimum limits, mean, median, standard deviation, and coefficient of variation were determined for the chemical properties analyzed for the 600 soil samples, as well as the lime requirements (LR) estimated for each of the calculation methods evaluated.

The mean values of LR obtained by each calculation method were compared by Student's t test, calculating the common variance (σ^2) when the F test (S^2_X/s^2_y) was not significant at 1 % probability. The simple linear correlation (Pearson) between liming requirements estimated by all calculation methods was also calculated, in which the correlation magnitude was considered high when the value of r was ≥0.750.

Furthermore, frequency distribution was calculated from the 600 recommendations of lime requirements (LR) estimated for each calculation method, conditioned to requirements of the coffee crop for Ca and Mg (X = 3.5, suggested by Alvarez V and Ribeiro, 1999), the need for providing Ca and Mg, i.e., $[X - (Ca^{2+} + Mg^{2+})]$, and the chemical characteristics of the soil (potential acidity: H+Al and CEC at pH 7.0, T).

RESULTS AND DISCUSSION

The analytical results of the soil samples were very diverse, with large differences between the maximum and minimum limits, and great variability (Table 2). The samples represented different soil types and diverse management types, demonstrating the adequacy of the database for the proposed study. Soil samples ranged from very acidic to close to neutrality, fertile soils and very low fertility soils with high and low buffer capacity, even when considering different interpretation tables, including those of Raij et al. (1997b), Alvarez V et al. (1999), and Prezotti et al. (2007).

Table 1. Calculation methods for determination of liming requirement (LR)

No.	Code	Form of calculation	Description
1	BSAT	LR = (Ve - Va)T/100	Ve and Va: expected and actual base saturation, in %; T: CEC pH 7, in $cmol_c\ dm^{-3}$.
2	MG1	$LR = Y \times Al^{3+} + [X - (Ca^{2+} + Mg^{2+})]$	Y: variable depending on soil buffer capacity and estimated from the P-rem (Alvarez V and Ribeiro, 1999); Al^{3+}: exchangeable aluminum in $cmol_c\ dm^{-3}$; X: crop requirement in Ca + Mg in $cmol_c\ dm^{-3}$ (X = 3.5 for coffee); $(Ca^{2+} + Mg^{2+})$: exchangeable contents of Ca + Mg, in $cmol_c\ dm^{-3}$.
3	MG2	$LR = Y [Al^{3+} - (m_t \times t/100)] + [X - (Ca^{2+} + Mg^{2+})]$	Y: variable depending on soil buffer capacity and estimated from the P-rem (Alvarez V and Ribeiro, 1999); Al^{3+}: exchangeable aluminum in $cmol_c\ dm^{-3}$; X: crop requirement in Ca + Mg in $cmol_c\ dm^{-3}$ (X = 3.5 for coffee); $(Ca^{2+} + Mg^{2+})$: exchangeable contents of Ca + Mg, in $cmol_c\ dm^{-3}$; m_t: maximum Al saturation tolerated by the crop, in % (m_t = 25 % for coffee); t: effective soil CEC.
4	ALG1	1) Lower value between BSAT and MG2 (LOWLR); 2) $[X - (Ca^{2+} + Mg^{2+})] \leq$ LOWLR; if true, LOWLR will be compared to H+Al; if false, HIGHLR will be compared to H+Al;. 3) LOWLR or HIGHLR ≤ H+Al; if true, it is the recommended rate; if false, it uses the H+Al value as LR in $Mg\ ha^{-1}$.	LOWLR and HIGHLR: lower and higher LR rate calculated by BSAT or MG2; X: crop requirement in Ca + Mg in $cmol_c\ dm^{-3}$ (X = 3.5 for coffee); $(Ca^{2+} + Mg^{2+})$: exchangeable contents of Ca + Mg, in $cmol_c\ dm^{-3}$; H+Al: soil potential acidity, in $cmol_c\ dm^{-3}$. Mathematical expression: $[X - (Ca^{2+} + Mg^{2+})] \leq$ LOWLR ≤ H+Al
5	ALG2	1) Higher value between BSAT and MG2 (HIGHLR); 2) HIGHLR ≤ H+Al; if true, it is the recommended rate; if false, it uses the H+Al value as LR in $Mg\ ha^{-1}$.	HIGHLR: higher LR rate calculated by BSAT or MG2; H+Al: soil potential acidity, in $cmol_c\ dm^{-3}$. Mathematical expression: HIGHLR ≤ H+Al
6	ALG3	1) LR by BSAT method (BSATLR); 2) $[X - (Ca^{2+} + Mg^{2+})] \leq$ BSATLR; if true, it is the recommended rate; if false, the $[X - (Ca^{2+} + Mg^{2+})]$ value will be compared with H+Al; 3) $[X - (Ca^{2+} + Mg^{2+})] \leq$ H+Al; if true, it is the recommended rate in $Mg\ ha^{-1}$; if false, it uses the H+Al value as LR in $Mg\ ha^{-1}$.	BSATLR: liming requirement calculated by base saturation method; X: crop requirement in Ca + Mg in $cmol_c\ dm^{-3}$ (X = 3.5 for coffee); $(Ca^{2+} + Mg^{2+})$: exchangeable contents of Ca + Mg, in $cmol_c\ dm^{-3}$; H+Al = soil potential acidity, in $cmol_c\ dm^{-3}$. Mathematical expression: $[X - (Ca^{2+} + Mg^{2+})] \leq$ BSATLR ≤ H+Al

LR: in $Mg\ ha^{-1}$ of limestone effective calcium carbonate equivalent (CCE) 100 % in total area and built up to a depth of 0.20 m.

In calculation of liming requirements (LR) for 600 samples, as expected, there were very discrepant results, and the base saturation method (BSAT) showed greater variability among the recommendations compared to other calculation methods (Table 3). This result is supported by the study of Sousa et al. (1989), who observed a greater variation of application rates when using the base saturation method compared to the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+}.

In contrast, Vasconcellos et al. (1994) observed that the BSAT method generated less pH variability after liming in a group of 45 soils from the Brazilian state of Minas Gerais. This result seems inconsistent, but it is specifically due to greater discrepancy in the recommendations that the BSAT method provides less variable pH values, because the estimated application rates have a closer relationship to the buffer capacity and T than those calculated by the other methods.

Considering a fixed value of V (Ve) for a given crop, there is a tendency for variations in T to promote proportional increases or reductions in the final recommended liming rates, generating more stable pH values. Based on this principle, authors such as Catani and Gallo (1955), Raij (1983), Sousa et al. (1989), and Vasconcelos et al. (1994) proposed linear models to estimate the soil pH, in which the base saturation (V) was the only independent variable.

Greater amplitude between the maximum and minimum recommended rates was provided by the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} using the MG1 calculation formula, which considers only the X and Y factors (Table 3). In contrast, Sousa et al. (1989) found an increased range of rates when using the BSAT method

Table 2. Maximum and minimum values, mean, median, standard deviation (s), and coefficient of variation (CV) of chemical properties determined in 600 soil samples considering coffee cultivation

Statistic	$pH(H_2O)$	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	SB	t	T	V	m	P-rem	OM
		mg dm^{-3}		cmol$_c$ dm^{-3}							%		mg L^{-1}	g kg^{-1}
Maximum	6.67	81.50	210.00	9.93	2.73	2.60	15.00	12.38	12.48	17.58	90.80	90.60	52.70	111.7
Minimum	3.86	0.10	1.00	0.02	0.01	0.00	0.20	0.06	0.16	0.79	1.50	0.00	1.60	3.8
Mean	5.02	1.78	24.28	1.12	0.29	0.28	3.73	1.48	1.76	5.21	28.54	21.04	34.04	21.5
Median	4.97	0.80	15.00	0.85	0.22	0.20	3.40	1.14	1.53	4.80	25.15	13.75	35.20	17.7
s	0.47	4.84	28.52	1.11	0.29	0.37	1.91	1.40	1.33	2.34	18.57	21.94	8.96	14.3
CV (%)	9.43	271.25	117.48	98.99	99.63	132.24	51.16	94.73	75.60	44.95	65.07	104.31	26.31	66.49

$pH(H_2O)$: pH in water, 1:2.5 (v/v); P and K: Mehlich-1 extractor; Ca^{2+}, Mg^{2+} and Al^{3+}: 1 mol L^{-1} KCl, H+Al and T: 0.5 mol L^{-1} $Ca(OAc)_2$, pH 7.0; P-rem: P in solution after stirring 60 mg L^{-1} of P in 10 mmol L^{-1} $CaCl_2$ for 1 h in a soil:solution ratio of 1:10. (Alvarez V et al., 2000); organic matter (OM): oxidation with potassium dichromate (Walkley-Black method).

Table 3. Maximum and minimum values, mean, median, standard deviation (s), and coefficient of variation (CV) of lime requirements estimated for six different forms of calculation, for 600 soil samples collected in coffee plantings, in regard to crop requirements and tolerance (V = 60 %, X = 3.5 and m_t = 25 %)

Statistic	Forms of calculating lime requirement					
	BSAT(1)	MG1(2)	MG2(3)	ALG1(4)	ALG2(5)	ALG3(6)
Maximum	8.61	10.59	8.45	8.06	8.61	8.61
Minimum	0.00	0.00	0.00	0.00	0.00	0.00
Mean	1.69	2.58	2.37	2.19	2.36	2.29
Median	1.61	2.67	2.43	2.30	2.40	2.39
s	1.22	1.39	1.21	1.15	1.24	1.14
CV (%)	72.01	54.12	50.91	52.52	52.37	49.62

(1) LR (Mg ha^{-1}) = $(V_e - V_a)T/100$; (2) LR = Y × Al^{3+} + [X - (Ca^{2+} + Mg^{2+})]; (3) LR = Y [Al^{3+} - (m_t × t/100)] + [X - (Ca^{2+} + Mg^{2+})]; (4) Algorithm that utilizes the lowest rate estimated by the classical methods of recommendation, with [X - (Ca^{2+} + Mg^{2+})] being the minimum limit of the rate and H+Al (cmol$_c$ dm^{-3}), the maximum LR limit; (5) Algorithm that utilizes the highest rate estimated by the classical methods of recommendation, with H+Al (cmol$_c$ dm^{-3}) being the maximum LR limit; (6) Algorithm that utilizes the BSAT method with the X - (Ca^{2+} + Mg^{2+})] as minimum limit of the rate and H+Al (cmol$_c$ dm^{-3}) as maximum LR limit.

compared to the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+}. However, these authors used a fixed Y value equal to 2. In this study, the value of Y ranged from 0 to 4 according to the P-rem value of the soil, as suggested by Alvarez V and Ribeiro (1999), which was certainly crucial in obtaining a greater range of doses.

The calculation method that generally recommended the largest LR was also MG1 (Tables 3 and 4). The principle used by this method is suitable since the first part of the formula seeks to neutralize Al^{3+}, and the second part of the formula seeks to increase the Ca^{2+} and Mg^{2+} content in the soil to meet the specific nutrient requirements of the crops. However, in calculating the lime requirement to neutralize Al^{3+}, it would be providing Ca and Mg that are not accounted for in the second part of the formula. Similarly, when estimating the amount of lime in order to supply the plants with Ca and Mg, the neutralization of Al^{3+} and H^+ performed by this fraction is disregarded, considering it only as a source of Ca and Mg and not carbonate, responsible for providing OH^-, which will correct the soil and increase the pH. Thus, there is the cumulative effect of the two fractions, as if one had no effect on what the other recommends, which can lead to excessive application rates in soils where the T and buffering capacity are low, as noted by Vasconcellos et al. (1994) in an incubation study using 45 soil samples.

The proposal of Alvarez V and Ribeiro (1999) to reduce the rate recommended by the first part of the formula in the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+}, adding the Al^{3+} saturation tolerated by the crops (m_t) (Table 1), i.e., Y [Al^{3+} - (m_t × t/100)], added better balance to the method, because the maximum rate and the average rate estimated from the MG2 formula were lower than those calculated by the MG1 formula (Tables 3 and 4).

The base saturation method (BSAT) in the average of 600 soil samples was that which recommended the lowest LR (Tables 3 and 4). In this method, the CEC of the soil at pH

Table 4. Test of t comparing the average lime requirement (LR) and correlation (r) between the liming recommendations calculated for six different forms to 600 soil samples collected in coffee plantings, in regard to crop requirements and tolerance (V = 60 %, X = 3.5 and m_t = 25 %)

Comparison/Correlation	t	r
Base saturation[(1)] with MG1[(2)]	-11.73**	0.7122**
Base saturation with MG2[(3)]	-9.69**	0.6630**
Base saturation with ALG1[(4)]	-7.33**	0.7421**
Base saturation with ALG2[(5)]	-9.46**	**0.9145****
Base saturation with ALG3[(6)]	-8.85**	**0.9142****
MG1 with MG2	2.77**	**0.9907****
MG1 with ALG1	5.21**	**0.9357****
MG1 with ALG2	2.85**	**0.8618****
MG1 with ALG3	3.87**	**0.8253****
MG2 with ALG1	2.59**	**0.9372****
MG2 with ALG2	0.12	**0.8391****
MG2 with ALG3	1.12	**0.8084****
ALG1 with ALG2	-2.44**	**0.8973****
ALG1 with ALG3	-1.52	**0.8818****
ALG2 with ALG3	0.99	**0.9881****

[(1)] LR (Mg ha^{-1}) = (V_e - V_a)T/100; [(2)] LR = Y × Al^{3+} + [X - (Ca^{2+} + Mg^{2+})]; [(3)] LR = Y [Al^{3+} - (m_t × t/100)] + [X - (Ca^{2+} + Mg^{2+})]; [(4)] Algorithm that utilizes the lowest rate estimated by the classical methods of recommendation, with [X - (Ca^{2+} + Mg^{2+})] being the minimum limit of the rate and H+Al ($cmol_c$ dm^{-3}), the maximum LR limit; [(5)] Algorithm that utilizes the highest rate estimated by the classical methods of recommendation, with H+Al ($cmol_c$ dm^{-3}) being the maximum LR limit; [(6)] Algorithm that utilizes the BSAT method with the X - (Ca^{2+} + Mg^{2+})] as minimum limit of the rate and H+Al ($cmol_c$ dm^{-3}) as maximum LR limit. **: significant at 1 % of probability. Bold numbers: high magnitude correlation (≥0.750).

7.0 (T) has a strong influence on the calculated LR value (Almeida et al., 1999). Although some of the 600 samples have a high T value, the average value of this characteristic was classified according to the table proposed by Alvarez V et al. (1999) as regular, trending downward. The median for this characteristic was 4.8 $cmol_c$ dm^{-3} (Table 2), which explains the relatively low application rates.

Lower LR rates were also obtained by Quartezani et al. (2013) from the base saturation method for the black pepper crop compared to the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents, despite using a higher V (70 %) and lower X (2.5) than those chosen for the present study.

ALG1 estimated lower LR rates than the two formulas of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} (MG1 and MG2) and also lower than ALG2 (Tables 3 and 4). Because ALG1 uses the lowest rate between BSAT and MG2 as a criterion, there is a tendency for the recommended average rates to be relatively lower, especially in relation to the MG1 formula.

Algorithms 1 and 2 used selection of the smallest and the largest LR rates, respectively, in their decision-making process, which explains the difference between them. However, algorithms 2 and 3 provided average LR rates equivalent to those calculated by MG2 and among each other (Tables 3 and 4), demonstrating that the rates estimated by these algorithms cannot be considered low compared to the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents since they were undoubtedly the average rates calculated by the BSAT and ALG1 methods.

The difference between the average rates recommended by algorithms 2 and 3 was so small that statistically it does not exist, but the ALG2 recommended an average rate higher than ALG1, which was not observed between ALG3 and ALG1 (Tables 3 and 4), indicating that only the use of X - (Ca+Mg) in ALG3 may slightly reduce the average rate in relation to the use of MG2 in ALG2.

The BSAT method showed no correlation with either of the formulas of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents (MG1 and MG2), but they had a high correlation with each other (Table 4), as expected. These results confirm the different theoretical bases that support the two methods. Whereas the first seeks to increase the soil base saturation (V), increasing the pH to approximated values and providing Ca and Mg in varying amounts according to T, the second method considers its two formulas (MG1 and MG2) in an attempt to directly neutralize an important soil acidity source, Al^{3+} (exchangeable acidity), increasing the pH and also providing adequate amounts of Ca and Mg to supply the plants (fixed for each species), which increases V as a function of T.

All algorithms were highly correlated with each other and with both formulas of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents (Table 4). This correlation was expected. The algorithms, despite differences of criteria in defining the rates, follow the same logical configuration, which explains the high association, although the average rates are a little different. All the algorithms have the X - (Ca + Mg) value as the lower limit of rates in the decision-making process. This is one of the principles of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents used in both formulas; therefore, the relationship between the algorithms and this method is clear and evident.

Among the three algorithms, only the ALG1 did not show high correlation with the SATB method (Table 4), despite its participation in the decision-making process.

When selecting the lowest rate as the input to ALG1, there is a tendency to select the rate calculated by the MG2 method. If the soil T is high, the rates calculated by the BSAT method are generally higher than those calculated by the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents, as reported by Faquin et al. (1998). In this case, the rate calculated by the MG2 method would be selected and compared with H+Al.

If the soil T is low, the rate calculated by BSAT will be lower than that calculated by the MG2 method, which would be the selected rate. However, in this situation, the selected rate tends to be smaller than X - (Ca + Mg), which leads to selection of the highest rate, and, in this case, it will again be calculated by the MG2 and compared with H+Al. This is indicated by the rates calculated with ALG1, where only 7.17 % were equal to those calculated by the BSAT method and 75.33 % equal to those calculated by the MG2 method. Thus, it is evident that the ALG1, which uses the lowest rate calculated among the classical methods of LR calculation, in fact follows the calculation principle of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents, with a somewhat biased decision-making process.

Algorithms 2 and 3 had high correlation with the BSAT method (Table 4), showing a more equitable decision-making process. For ALG2, which uses the higher rate of BSAT and MG2 as the input, if the soil T is high, the selected rate will usually be that calculated by BSAT, which must satisfy the plant requirements of Ca + Mg and will be less than H+Al.

In contrast, if the soil T is low, the rate generally selected will be the calculated by the MG2, which will satisfy the plants in relation to Ca + Mg, but will be limited by H+Al. For ALG3, which has the BSAT method and the second part of the formula of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} in its decision-making process, i.e., X - (Ca + Mg), when the T is low and the rate calculated for BSAT is not sufficient to supply the plants with Ca + Mg, it uses the value of X - (Ca + Mg) as the LR rate, thus avoiding the cumulative effect caused by the two parts of the formula of the original method.

ALG3 proved to be well balanced, with 26.17 % of the recommended rates equal to those estimated by the BSAT method, while 40.17 % of the rates were equal to those provided by the MG2 method, even when using only the portion of the formula intended to elevate the levels of Ca^{2+} and Mg^{2+} in the soil: X - (Ca + Mg).

Considering the recommendation frequencies, in 73.83 % of the cases, the BSAT method would not be able to estimate sufficient amounts of lime to supply the plants with Ca + Mg (Table 5) when considering the Ca + Mg need (X) for 3.5 $cmol_c\ dm^{-3}$ as a well calibrated estimate for the coffee crop. In fact, the accuracy of the nutrient demand value is not of great importance to this study. If X were slightly higher or lower, the base saturation method would still be the calculation method providing the lowest percentage of appropriate rates to meet the Ca + Mg demands of the plant, considering the database used in the present study.

Table 5. Distribution frequency of liming requirements (LR) calculated by six different forms for 600 soil samples collected in coffee plantings, in regard to crop requirements and tolerance (V = 60 %, X = 3.5 and m_t = 25 %), conditioned on coffee requirements in Ca^{2+} and Mg^{2+} (X) and the chemical properties of the soil (H+Al and T)

Method	Considering Ca and Mg (X) requirement				Considering chemical features of the soil		
	LR = 0	0 < LR < [X - (Ca + Mg)]	[X - (Ca + Mg)] ≤ LR < X	LR ≥ X	LR ≤ H+Al	H + Al < LR ≤ T	LR > T
	%[1]						
BSAT[2]	7.00	73.83	20.84	5.33	100.00	0.00	0.00
MG1[3]	3.50	0.00	86.00	14.00	78.17	13.16	8.67
MG2[4]	5.50	0.00	91.83	8.17	80.17	13.00	6.83
ALG1[5]	5.50	17.67	75.66	6.67	100.00	0.00	0.00
ALG2[6]	2.17	17.67	73.33	9.00	100.00	0.00	0.00
ALG3[7]	2.17	17.67	77.00	5.33	100.00	0.00	0.00

[1] % relative to total of 600 soil samples considering coffee plantations used in the study; [2] LR ($Mg\ ha^{-1}$) = (V_e - V_a)T/100; [3] LR = Y × Al^{3+} + [X - (Ca^{2+} + Mg^{2+})]; [4] LR = Y [Al^{3+} - (m_t × t/100)] + [X - (Ca^{2+} + Mg^{2+})]; [5] Algorithm that utilizes the lowest rate estimated by the classical methods of recommendation, with [X - (Ca^{2+} + Mg^{2+})] being the minimum limit of the rate and H+Al ($cmol_c\ dm^{-3}$), the maximum LR limit; [6] Algorithm that utilizes the highest rate estimated by the classical methods of recommendation, with H+Al ($cmol_c\ dm^{-3}$) being the maximum LR limit; [7] Algorithm that utilizes the BSAT method with the X - (Ca^{2+} + Mg^{2+})] as minimum limit of the rate and H+Al ($cmol_c\ dm^{-3}$) as maximum LR limit.

The total amount of Ca + Mg added by liming is not considered in the calculation principle of the BSAT method, since in soils with low T, it can be greatly reduced, even considering a stipulated value of the expected V (Ve) of 60 %, as suggested by Alvarez V and Ribeiro (1999). When using a Ve of 50 %, as suggested by Raij et al. (1997a) for coffee, a larger percentage of situations would be expected where LR rates did not adequately supply the plants with Ca and Mg.

It is important to note that in 76 % of the cases where the BSAT method would not be able to properly supply the plants with Ca and Mg, the value of T was less than or equal to 5.0 $cmol_c$ dm^{-3}. In contrast, in 100 % of situations where the BSAT method would adequately supply the plants with Ca and Mg, the value of T was always greater than 5.0 $cmol_c$ dm^{-3}. Authors such as Raij et al. (1997a) recognized the limitation of this method in relation to the amount of nutrient added via liming since, even when recommending in increase in V of up to 50 % for the coffee crop, they also indicated elevation of the soil magnesium content to a minimum of 0.5 $cmol_c$ dm^{-3}. Despite these findings, the BSAT method showed very low possibility of recommending rates that could cause overliming, since 100 % of the recommendations were lower than the soil H+Al values (Table 5).

The method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents, considering the two forms of calculation used (MG1 and MG2), would provide an adequate supply of Ca + Mg in 100 % of the cases (Table 5). This demonstrates the efficiency of this method when seeking to supply Ca and Mg liming if the value of X is well calibrated for the crop in question. However, when using MG1 and MG2, the same method provided rates higher than the H+Al in 21.83 and 19.83 % of the cases, and greater than T in 8.67 and 6.83 % of the cases, respectively (Table 5), which can lead to very high soil pH values. This is not a rule, because there are many other factors involved in elevation of soil pH from liming in addition to the application rate or its ratio in relation to H+Al and T, but, undoubtedly, an excessive increase in soil pH may occur in some situations when using this method, as observed by Vasconcellos et al. (1994).

Excessive liming is as harmful as high acidity, and the former is even more difficult to correct (Alvarez V and Ribeiro, 1999). When soil pH exceeds suitable values, precipitation of various nutrients, such as P, Zn, Fe, Cu, and Mn occurs, in addition to predisposition to damage of soil physical properties (Lacerda et al., 2006).

It should be noted that in 100 % of the cases where the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents recommended application rates greater than H+Al, the value of T was less than 4.7 $cmol_c$ dm^{-3}. This result is very similar to the value of 4.0 $cmol_c$ dm^{-3} for T, which, according to Sousa et al. (1989), is the lower limit for this feature where the method in question results in overliming.

Thus, there is a clear problem of classical methods (BSAT, MG1, and MG2) for recommending LR rates for soils whose T value is less than 5.0 $cmol_c$ dm^{-3}. In this case, although the BSAT method would tend to not adequately supply plants with Ca and Mg, the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents would tend to cause overliming.

This certainly will not happen for all situations where the soil T is lower than 5.0 $cmol_c$ dm^{-3}, since many other factors are involved, but one should be alert for soils that have this pattern. The calculation algorithms of LR can reduce these problems, because they ensure the supply of Ca and Mg while seeking to maintain an acceptable level of soil pH elevation.

The three algorithms studied provided recommendation of rates lower than or equal to H+Al (Table 5) since they show the value of H+Al as the maximum rate limit, which tends to reduce the possibility of overliming to very low levels. In addition to having this important property, the algorithms stood out for supplying the plants with Ca and Mg in 82.33 % of the cases, a much higher percentage than the BSAT method, which would supply the plants in 26.17 % of cases (Table 5).

The difference among the three algorithms regarding the frequencies of recommendation consists solely in the fact that ALG3 concentrated more recommendations between the value of X - (Ca + Mg) and the value of X. This demonstrates that ALG3 is more balanced, avoiding the waste of applying lime rates exceeding that strictly necessary, which tends to increase the return on investment of this practice.

The constant work of calibrating the V and X values for different soils, crops, and management situations is essential, and ALG3 is even more suitable as these calibrations are refined.

CONCLUSIONS

The methods of base saturation and Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents provided estimates of the lowest and highest liming requirement rates, respectively.

In soils with a low value of CEC at pH 7, the base saturation method may not suitably supply the plants with Ca and Mg in many situations, while the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} concentrations can provide calculation of rates that may cause a rise in pH above the appropriate range.

Insertion of the maximum saturation of aluminum tolerated by the crop (m_t) in the first part of the formula of the method of Al^{3+} neutralization and elevation of Ca^{2+} and Mg^{2+} contents reduces the recommended rates of liming requirements, making the method more balanced.

Among the methods studied for calculating the liming requirement, the algorithm that proposed reaching a defined base saturation with assurance of an appropriate supply of Ca and Mg, and presenting the final rate limited to the H+Al value, proved to be the most efficient form of calculation, and its use can be recommended for countless crop situations.

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